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Author(s): Lindell, Rene & Hakonen, Pertti J.

Title: Noise properties of the Bloch oscillating transistor

Year: 2005

Version: Final published version

**Please cite the original version:**

Lindell, Rene & Hakonen, Pertti J. 2005. Noise properties of the Bloch oscillating transistor. Applied Physics Letters. Volume 86, Issue 17. 173507/1-3. ISSN 0003-6951 (printed). DOI: 10.1063/1.1919392

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## Noise properties of the Bloch oscillating transistor

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Citation: [Applied Physics Letters](#) **86**, 173507 (2005); doi: 10.1063/1.1919392

View online: <http://dx.doi.org/10.1063/1.1919392>

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# Noise properties of the Bloch oscillating transistor

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(Received 21 October 2004; accepted 9 March 2005; published online 21 April 2005)

We have measured the current noise spectral density of the Bloch oscillating transistor as a function of current gain. We find, as expected from theory and simulations, that the equivalent input noise that shows up in the output is less than the shot noise of the normal-insulating-superconductor tunnel junction (base junction). At the optimal operating point we find a reduced input current noise of  $1.0 \text{ fA}/\sqrt{\text{Hz}}$  and a corresponding noise temperature of  $0.4 \text{ K}$ . The differential current gain at the same point is as large as 30 and the power gain amounts to 35. © 2005 American Institute of Physics. [DOI: 10.1063/1.1919392]

The Bloch oscillating transistor (BOT) is a mesoscopic amplifier with various operating modes.<sup>1–3</sup> It can function as a current amplifier with considerable current and power gain in its stable operating region. The BOT has an input impedance which can relatively easily be tuned in the  $100 \text{ k}\Omega$ – $100 \text{ M}\Omega$  range thus facilitating impedance matching and filling the gap between the low impedance SQUID and the high-impedance single electron transistor (SET). Some possible applications for the device are first stage amplification of small currents for current standard metrology and current readout device for quantum electronics. In these applications, both the noise at the output, which sets the limit for accuracy of the device, and the back-action noise must be considered.

In this letter we discuss measurements of the noise properties of the BOT. We have measured the output current noise as a function of current gain and observe saturation of the noise at large gains. We find that the equivalent input noise is by a factor of 4 smaller than the shot noise of the input tunnel junction, resulting in a corresponding noise temperature of  $0.4 \text{ K}$ .

The BOT is a transistor like three-terminal device. The investigated sample consisted of an  $\text{Al}-\text{Al}_x\text{O}_x-\text{Al}$  Josephson junction (JJ) as emitter, an  $\text{Al}-\text{Al}_x\text{O}_x-\text{Cr}-\text{Cu}$  normal-insulating-superconductor tunnel junction (NIS) as base and a chromium resistor as collector (see Fig. 1 for the schematic layout). We found that the  $7 \text{ nm}$  thick chromium layer in the NIS junction made it more durable and increased sample yield. A more detailed account of the fabrication and characteristics of the BOT is given in Ref. 1.

In short, the BOT is based on the dynamics of the band model of the Josephson junction, which results from the competition of the charging energy  $E_C = e^2/2C$  and the Josephson coupling energy  $E_J$ .<sup>4</sup> The nondissipative supercurrent flows by means of Bloch oscillations in the lowest band of the JJ. Occasionally, the JJ undergoes Zener tunneling to a higher band and becomes Coulomb blockaded, which leads to a halt in supercurrent flow. A small applied quasiparticle current ( $I_B$ ) through the base NIS junction can drive the JJ back down to the first band thereby resuming the Bloch oscillation. Current amplification is then given by the number of Bloch oscillations triggered by one quasiparticle. Hence, this amplification mechanism which is based on the transi-

tion between the current-carrying and blockaded states also gives rise to a characteristic two-level noise.<sup>5</sup>

The BOT can have many different operating modes depending on the resistances of the tunnel junctions, the junction capacitances, the collector resistance  $R_C$  and the sign of the bias voltage  $V_C$ . Here, we consider the case of a BOT in the normal operating mode (corresponding to negative  $V_C$  in Fig. 1), where we find a maximum current gain of 30 and power gain of 35.

The measurement setup is as shown in Fig. 1 and the BOT parameters are listed in Table I. The sample is mounted in a rf-shielded copper enclosure and attached to the mixing chamber of a plastic dilution refrigerator with a base temperature of  $34 \text{ mK}$ . The sample holder includes  $70 \text{ cm}$  long Thermocoax cables for filtering high frequency noise. To measure current noise we use a scheme where the current noise at the collector is converted into voltage noise with the resistor  $R_{CC}$  (a surface mount resistor located on the sample holder). The voltage over the resistor is measured by two LI-75A low noise preamplifiers and the outputs  $V_1(t)$  and  $V_2(t)$  are fed into an HP 89410A vector signal analyzer and cross correlated. The cross-correlation method<sup>6</sup> reduces the excess noise by a few dB compared to using only one amplifier without cross correlation.

The BOT base is current biased by a large resistor  $R_{\text{bias}} = 1 \text{ G}\Omega$ . For the power gain measurement, an ac-signal ( $17.5 \text{ Hz}$ ) is applied through a capacitance  $C_C = 1 \text{ nF}$  to the base lead. This way, we bypass the large  $R_{\text{bias}}$  and have enough bandwidth for lock-in measurement of the differential power gain  $\eta = (dV_{CC}/dI_B)^2 / (R_{CC}Z_{\text{in}})$ . The ac-current

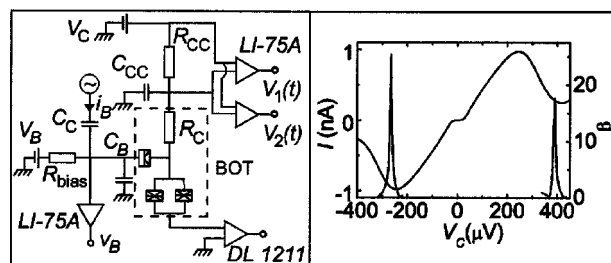


FIG. 1. Left: Measurement setup for the cross correlation and power gain measurements. The BOT circuit is indicated by the dashed box. The BOT and the resistor  $R_{CC}$  are at  $34 \text{ mK}$  while the rest of the components are at room temperature. Right:  $I$ - $V$  characteristic and current gain for  $I_B = 60 \text{ pA}$ . The Coulomb blockade is clearly seen as the environmental resistance  $R_C \gg R_Q = 6.45 \text{ k}\Omega$  and  $E_J \ll E_C$ .

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TABLE I. BOT parameters.  $R_{\text{NIS}}$  and  $R_{\text{JJ}}$  are the normal state resistances of the NIS and JJ tunnel junctions. Resistances are given in units of  $\text{k}\Omega$  and energies in Kelvins.

$R_{\text{NIS}}$	$R_{\text{JJ}}$	$R_C$	$R_{\text{CC}}$	$E_J$	$E_C$	$E_J/E_C$
90	24	188	100	0.28	0.93	0.3

measurement at the base, however, will be affected by the capacitance of the leads (mainly from the Thermocoax filters) which is estimated to  $C_B \sim 500$  pF. Hence, the BOT input impedance is given by  $Z_{\text{in}} = zZ_C/(Z_C - z)$ , where  $z = dv_B/di_B$  is the measured ac-differential impedance at the base and  $Z_C = 1/(\omega C_B)$  is the impedance of the stray capacitance of the leads at the measurement frequency  $\omega$ . We can thus measure the power transfer from input (the base) to the resistor  $R_{\text{CC}}$ , which acts as the load for the BOT amplifier.

After cross correlating the signal from the LI-75A amplifiers (measurement time 5–10 min.), the voltage noise of the amplifiers is practically eliminated and we are left with the BOT output noise, the back-action current noise of the LI-75A+ any spurious noise source not accounted for. The residual noise on the  $R_{\text{CC}} = 100$   $\text{k}\Omega$  resistor was found to be  $2.6$   $\text{nV}/\sqrt{\text{Hz}}$  (measured at unity gain and low current through BOT). We convert the measured noise to equivalent noise at the input by the following formula:

$$i_{n_{\text{in}}}^2 = (i_{n_{\text{out}}}^2 - i_{n_{\text{res}}}^2)/\beta^2, \quad (1)$$

where  $i_{n_{\text{res}}}$  is the residual noise,<sup>7</sup> and  $\beta$  is the current gain.

In Fig. 2 we present the results of the cross-correlation measurement: output noise as a function of current gain. Here, the base current is held constant at  $I_B = 60$  pA and the operating point is varied in the region of the current gain peak for  $V_C = [-295, -265]$   $\mu\text{V}$  (see Fig. 1). The gain of the BOT depends highly on the base current and  $E_J/E_C$ . The maximum gain was achieved for  $E_J/E_C = 0.3$ , which was the maximum ratio for this sample and all the presented results were observed at this value.

The measuring equipment was sensitive to vibration noise, which made the noise floor unstable. Hence, the BOT noise was taken as the average value of the noise floor at 1.3 and 1.9 kHz. Figure 2 shows that for increasing gain the output noise saturates and, in fact, from  $\beta = 4$  onward becomes less than the shot noise generated at the base NIS junction (with  $\beta = 24$ , the amplified shot noise would be  $100$   $\text{fA}/\sqrt{\text{Hz}}$ ). The BOT noise behaves like an intrinsic two-level noise acting at the output. An increasing current gain with a simultaneously saturating output noise means that the equivalent input noise must be decreasing. For  $\beta = 24$ , the ratio  $i_{n_{\text{in}}}/\sqrt{2eI_B}$  becomes less than 1:4. The reason for the reduction can also be understood by noting that part of the tunneling electrons in the NIS junction gives rise to intra-band transitions in the JJ (as opposed to the interband transitions, responsible for the BOT operation) and thus only part of the shot-noise current is amplified. Hence, as  $\beta$  grows with growing  $I_B$  the fraction of  $I_B$  that causes interband transitions drops.

The noise temperature  $T_n = i_{n_{\text{in}}}^2 Z_{\text{in}}/k_B$  of the BOT is a relevant measure for quantifying its performance relative to other amplifiers.<sup>8</sup> The input impedance  $Z_{\text{in}}$  was measured with the scheme in Fig. 1 using lock-in amplifiers. We found that  $Z_{\text{in}} \approx 1.4\beta(R_C + R_{\text{CC}})$ , which is close to a simple black-

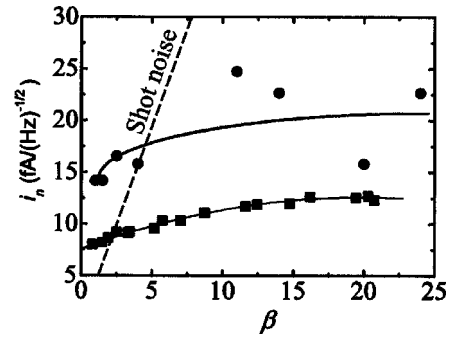


FIG. 2. Experimental (●) and simulated (■) output current noise spectral density as a function of the current gain for base current  $I_B = 60$  pA. Fitted lines are to guide the eyes.

box model which yields a prefactor of 1. In Fig. 3 we present noise temperature versus current gain, together with results from simulations using time-dependent  $P(E)$ -theory as described in Ref. 3. In both cases the behavior is  $\sim 1/\beta$ . The experimental exponent is  $-1.0 \pm 0.1$  and the simulated  $-1.2$ . At the largest current gain,  $\beta = 24$ , we found an input referred current noise of  $1.0$   $\text{fA}/\sqrt{\text{Hz}}$  and a noise temperature of  $0.4$  K, while the simulated noise temperature was as low as  $100$  mK. The increasing discrepancy between the experiment and simulation can be attributed to heating effects in the chromium resistor. With growing  $\beta$ , the JJ current increases and heats up the chromium resistor from  $200$  to  $300$  mK over the region  $\beta = 4$ – $24$ . Consequently, the thermal noise increases and the effective noise temperature of the device grows by  $\sim 150$  mK.

Even though the output noise current and the noise temperature seem quite small, the back-action noise at the amplifier base is, however, still governed by the shot noise of the base junction. In this particular case, the base current  $I_B = 60$  pA gives rise to a voltage fluctuation of  $40$   $\text{nV}/\sqrt{\text{Hz}}$ . Correlation between tunneling events in the two junctions lowers the shot noise somewhat. The theoretical minimum Fano factor is  $0.5$  but in simulations, for the currents used here, the factor is  $0.8$ – $0.9$ . Simulations also show that a device with a larger  $R_C$  should have a larger current and power gain already for smaller base currents; thus leading to a reduced back-action noise but, then the input impedance and, consequently, the optimal source impedance will increase.

One of the attractive features of the BOT is that it is quite insensitive to background charge fluctuations. This is seen in the absence of  $1/f$  noise for small base currents. The  $1/f$  noise becomes clearly visible only for high values of  $I_B$

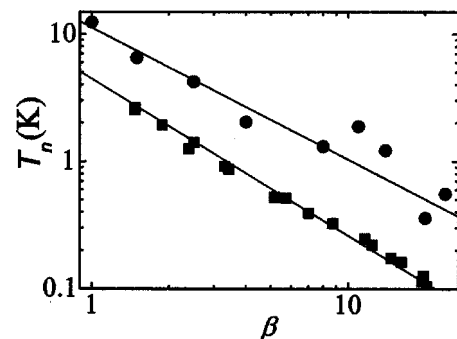


FIG. 3. BOT input referred noise temperature as a function of current gain  $\beta$  from the experiment (●) and simulation (■).

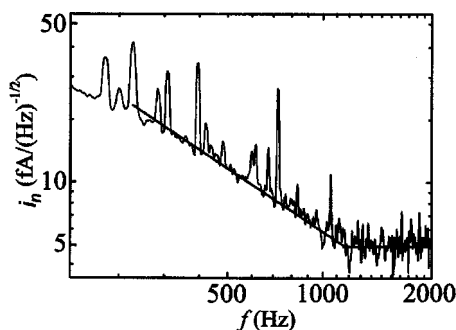


FIG. 4. Input referred current noise spectrum for  $I_B=400$  pA. The  $1/f$  corner frequency is found at the vertex of the two lines.

and in regions of current amplification. Figure 4 shows the current noise spectrum for  $I_B=400$  pA. In terms of power, the  $1/f^\alpha$  exponent is 2.0 around 500 Hz. For lower frequencies and currents the exponent goes down to 1.3. This variation of the exponent between 1.3 and 2.0 is usual in our noise spectra for the BOT. The corner frequency is found around 1 kHz, which is just below the circuit cutoff at 3 kHz. From the fact that no  $1/f$  type of noise could be found for low base currents, it can be reasoned that the  $1/f$  noise is generated in the NIS junction and not in the Josephson junction. One possible source of this noise could be charge traps in the extra chromium–aluminum–oxide interface.

In summary, we have shown that the BOT noise versus gain characteristics are qualitatively similar to the theoretical prediction. We found that the output noise saturates with increasing gain, which implies an input referred noise of

$1.0 \text{ fA}/\sqrt{\text{Hz}}$  and a noise temperature of 0.4 K at an operating point where  $I_B=60$  pA. At the same operating point, the device has a current and power gain of about 30. The results show that the BOT is a promising candidate for on-chip first-stage amplification for nanoelectronics.

The authors acknowledge fruitful discussions with Juha Hassel, Heikki Seppä, Julien Delahaye, Mika Sillanpää, Edouard Sonin, and Mikko Paalanen. Financial support by the Academy of Finland, by TEKES, and by the Large Scale Installation Program ULTI-III of the European Union (HPRI-1999-CT-00050) is gratefully acknowledged.

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<sup>7</sup>Residual noise was measured at an operating point where the noise contribution due to the BOT was negligible. After cross correlating the signals from the amplifiers the largest remaining noise source is the current noise of the LI-75As.

<sup>8</sup>Difference of factor of 2 from the usual noise temperature definition is due to the fact that the input current and voltage noises of the BOT are fully correlated and add in amplitude, not in power.